Precipitation gradient and crop management affect N_2O emissions: simulation of mitigation strategies in rainfed Mediterranean conditions

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Abstract

In Mediterranean areas high precipitation variability and crop dependence on soil water availability make the interaction between climate and agricultural management a key issue for mitigating N_2O emissions. In this study we used the STICS model to capture the effect of a water deficit gradient and precipitation variability on N_2O emissions and mitigation strategies (i.e. N fertilizer type, grain legumes introduction in crop rotations and crop residues management) in a rainfed Mediterranean transect (HWD-Senés, MWD-Selvanera and LWD-Auzeville, i.e. high, medium and low water deficit, respectively). The model was first tested against a database of daily N_2O fluxes measured during twelve growing seasons of winter crops at the LWD site. Several scenarios were then run on each site, always over 9 successive growing seasons to take into account precipitation variability. STICS showed a good ability to simulate the driving variables of N_2O fluxes at the daily time scale. The mean observed and simulated cumulative emissions during the growing season were 0.71 and 0.82 kg N_2O-N ha^{-1}, respectively. The simulated N_2O emissions (mean of all scenarios) decreased with increasing water deficit being 2.51, 0.65 and 0.26 kg N_2O-N ha^{-1} yr^{-1} for LWD-Auzeville, MWD-Selvanera and HWD-Senés, respectively, which is consistent with published results. The lower N_2O emissions in the driest sites were not only related to lower fertilization rates but also to other factors associated with the Mediterranean characteristics, particularly, the drier water regime. Simulated N_2O emissions were highly sensitive to the interannual variability of the climatic conditions. According to the simulations, urea fertilizer would lead to slightly higher N_2O emissions (+6 and +8%) than ammonium- and calcium nitrate, respectively. The incorporation of winter pea in the traditional cereal-based Mediterranean rotations would reduce by ca. 22% the N_2O emissions in HWD-Senés without changing wheat yields. Differently, in MWD-Selvanera and LWD-Auzeville, N_2O emissions would remain unchanged since the emissions associated to the decomposition of low C:N ratio pea residues would

counteract the lower application of N fertilizer. The systematic removal of crop residues at LWD-Auzeville would decrease the N_2O emissions by 20%. However, this practice seems not recommendable if tillage is practiced due to the concomitant decrease of soil organic matter, fact that would worsen the C footprint of the system and increase the susceptibility to soil erosion. Our work highlights the interest of combining experimental and modelling approaches to account for climatic variability and evaluate long-term effects of N_2O mitigation practices under Mediterranean conditions.

Keywords

Cereal; Grain legumes; Mitigation strategies; N fertilizer type; Crop residue management; STICS model.

1. Introduction

The Mediterranean climate is defined by warm to hot, dry summers and mild to cool, wet winters. It is located between 30 and 45º north and south latitudes. Although it presents a large variability between regions, its common feature is the presence of a severe water deficit during the summer months, while in winter months rainfall usually exceeds evapotranspiration, leading to a soil water recharge (López-Bellido, 1992). Rainfall presents a high intra- and inter-annual variability, with an increasing trend of extreme events in spring and summer months (Ramos and Martínez-Casasnovas, 2006). Crops in the non-irrigated Mediterranean areas strongly depend on the amount of water stored in soil during the recharge period (i.e. September to January) (Cantero-Martínez, et al., 2007), and cropping systems are mainly based on winter cereals, given their cycle synchrony with water availability (López-Bellido, 1992; Álvaro-Fuentes et al., 2009). Crop dependence on soil water availability makes the interaction between climate and agricultural management a key issue both for crop production and N_2O emissions mitigation.

Nitrous oxide is a powerful greenhouse gas with a global warming potential (GWP) 265 times greater than carbon dioxide (IPCC, 2013). Besides its strong implication in radiative forcing, N_2O also influences the depletion of the ozone layer in the stratosphere (Crutzen, 1974). Soil N_2O emissions are the result of the nitrification-denitrification processes (Bremner, 1997). They are known to be highly dependent on mineral nitrogen availability and soil moisture. The continuous increase in fertilizer use since the invention of the Haber-Bosch process of industrial N_2 fixation has exacerbated N_2O emissions from soils (Gruver and Galloway, 2008). Nitrogen management has been traditionally oriented towards optimizing the use of N by the crop. In some areas, a significant fraction of N fertilizer is still applied before sowing, which, especially for winter crops, can enhance leaching losses in the rainiest locations and/or lead to an overuse of soil water due to the increase in plant transpiration during the vegetative stages. Because it remains difficult to optimize N fertilization strategies to crop needs under variable water stress conditions, the resulting periods of high mineral N availability can also induce N losses as N_2O. Different fertilization strategies have been tested as a means of mitigating N_2O emissions in the Mediterranean agroecosystems. Among them, (i) the adaptation of N fertilizer application to crop needs, (ii) the split of N fertilizer at key crop development stages, (iii) the use of organic and synthetic fertilizers, and (iv) the use of nitrification inhibitors (e.g. Aguilera et al., 2013; Meijide et al., 2007, 2009; Plaza-Bonilla et al., 2014a; Sanz-Cobeña et al., 2012; Vallejo et al., 2001). Although there is a growing set of knowledge about the impact of fertilization management on N_2O emissions in the Mediterranean areas, the site and temporal specificity of the studies carried out limit our ability to establish general rules for optimized management practices at the regional level, according to climate idiosyncrasies. In particular it would be useful to better know, among fertilization management strategies, which ones are more strongly affected by a more or less pronounced aridity or precipitation variability. Process based models are complementary to site specific studies in that they have the potential to integrate a range of processes and to study the interactions between pedoclimatic conditions and agricultural management practices (De Antoni-Migliorati et al., 2015; Doltra et al., 2015).

The objectives of this study were to i) compile a dataset of N_2O emission obtained in Mediterranean conditions and evaluate the ability of a simulation soil-crop model (STICS) to predict the observed fluxes, ii) evaluate its ability to capture the effect of a gradient in mean precipitation and year to year irregularity on N_2O emissions in a Mediterranean transect and iii) to test the efficiency of several agricultural management strategies for mitigating N_2O emissions along such a climatic gradient.

2. Materials and methods

2.1. Selection of a representative precipitation transect under Mediterranean conditions

Three locations representative of the Mediterranean climate were chosen according to a rainfall gradient: Senés, Selvanera and Auzeville (Table 1). This choice was based on (i) the availability of soil N_2O emission data in (or close to) each location to validate the STICS model or check the range of simulated values (Plaza-Bonilla et al., 2014a; Peyrard et al., 2016) and (ii) the presence of cropping systems representative of dryland Mediterranean agriculture. Senés (NE Spain), representative of the Monegros county, was chosen as the lower yield potential threshold given its low annual precipitation (336 mm), large potential evapotranspiration (1250 mm) and long water deficit period (Fig. 1). The upper threshold of the transect was located in Auzeville (SW France) which represents one of the most northern latitude under Mediterranean climate influence and the smallest water deficit (with annual precipitation and potential evapotranspiration values of 685 and 905 mm, respectively) (Fig. 1). Finally, Selvanera (NE Spain) was chosen given its intermediate water deficit, annual precipitation (450 mm) and potential evapotranspiration (800 mm) (Fig. 1). Site and soil characteristics of each location of the transect are shown in Table 1. The average productivity of winter cereal (i.e. wheat or barley) is around 1000, 3200 and 5500 kg ha^{-1} for Senés, Selvanera and Auzeville, respectively (Plaza-Bonilla et al., 2014b, 2016).

Traditional cropping systems consist of barley (*Hordeum vulgare* L.) monocropping or a barley-wheat (*Triticum aestivum* L.) rotation in Senés, winter cereal rotations including winter pea (*Pisum sativum* L.) and/or rapeseed (*Brassica napus* L.) in Selvanera and wheat – sunflower (*Helianthus annuus* L.) rotation in Auzeville. Only a small proportion of the farmers includes grain legumes such as vetch (*Vicia sativa* L.) and winter pea (*Pisum sativum* L.) in the rotations in Senés and Selvanera given the high probability of harvest loss due to water stress and doubtful economic benefit (Álvaro-Fuentes et al., 2009). Soil management in the area of Senés and Selvanera is based on reduced tillage (i.e. vertical tillage with chisel ploughs and/or cultivators) and no-tillage (Álvaro-Fuentes et al., 2009; Angás et al., 2006). In turn, in the area surrounding Auzeville, traditional soil management is based on conventional, inversion tillage with moldboard plough (Plaza-Bonilla et al., 2016).

2.2. Overview and evaluation of the soil-crop model STICS for N_2O emissions.

The soil and crop model STICS (Brisson et al., 1998, 2002, 2008) is a one-dimensional daily time-step model which simulates plant growth as well as water, C and N cycles over one or several growing seasons. It considers several soil layers with specific properties and uses pedoclimatic characteristics and management practices as inputs for the simulation. The description of the physical and biological processes occurring in the soil-crop system mostly relies on a set of generic parameters which are considered not specific of a context of study and thus are not subject to any calibration. This reduces the risk of introducing bias through specific calibration which often relies on limited or uncertain data when comparing scenarios over a range of contexts. Recently, Coucheney et al. (2015) evaluated the ability of the STICS model to simulate different plant, water and nitrogen outputs over a wide range of pedoclimatic conditions and N fertilization rates in France. Despite the large diversity of conditions considered and the use of the standard set of model parameters, simulated results were shown to be good enough to allow useful predictions of crop and soil variables when the objective is to compare a variety of pedoclimatic and agronomic situations.

The simulation of N_2O emissions in STICS relies on the concepts described in Bessou et al. (2010). Nitrification and denitrification processes, and the N_2O emissions associated to each process, are simulated separately. Coupling of nitrification and denitrification exists through the production of nitrate by nitrification, which then serves as substrate for denitrification and N_2O emissions associated to this pathway. Processes are described using a functional approach which is similar to that used in other models like DayCent or Ecosse.

Nitrification rate is considered to be proportional to NH_4^+ content, which proved to be a good approximation over the typical range of ammonium content in soil. It is affected by temperature, increasing until an optimum rate at 32.5°C and then decreasing again (Benoit et al., 2015). Water filled pore space (WFPS) strongly influences the rate of nitrification: nitrification increases until field capacity is reached, then decreases because of the decline of soil aeration (Khalil et al., 2004). In the context of the study, pH does not constrain nitrification rate as pH levels are in the high range. N_2O emission associated to the nitrification pathway is calculated as a variable fraction of the nitrification rate. That fraction remains low for WFPS values below 60% (0.16-0.29%) but strongly increase with WFPS afterwards to reach a maximum of 2.56% at 100% WFPS as a consequence of the resulting decline in oxygen availability (Khalil et al., 2004).

Denitrification is calculated as the product of a soil dependent potential rate and functions expressing the effects of nitrate concentration, soil temperature and soil water content. Denitrification rate increases with NO_3^- content following a Michaelis-Menten kinetics with a half maximum constant of 215 mg NO_3-N l^{-1} which, depending on soil water content, corresponds to 20-60 mg NO_3-N kg^{-1} (Bessou et al., 2010). Denitrification rate also increases with temperature over most of the typical range of temperature as the optimum rate is 47°C (Benoit et al., 2015). As in the NEMIS model (Hénault and Germon, 2000), denitrification rate is null when WFPS is below a threshold which default value is 62% and then increases exponentially with WFPS. N_2O emission from denitrification is calculated as a variable fraction of the denitrification rate which mainly depends on pH and WFPS. Acid pH strongly inhibits N_2O reduction to N_2 (Rochester, 2003). In the model, the N_2O end-product ratio of denitrification increases with pH decreasing from 9.2 to 5.6. For pH values below 6, denitrification has N_2O as main end-product. Finally, soil water content values close to saturation favor N_2O reduction to N_2. This is due to the development of anoxia (Vieten et al., 2008) and to the increase in the residence time of N_2O into the soil associated to lower gaseous diffusion rates. This effect is taken into account through a linear decrease of the denitrification end-product ratio between the threshold WFPS for the onset of denitrification and maximal soil saturation (Bessou et al., 2010).

Observed data from the multi-year MicMac low input cropping systems experiment located in Auzeville (SW France), which includes intensive (i.e. daily) N_2O emissions measurements, were used to evaluate the ability of the STICS model in simulating N_2O emissions, in complement to simple comparison of the range of values of emissions for the two other sites. The Auzeville experiment compares three cropping systems which differ in nitrogen rates, pesticide use and cover crops frequency in a randomized design with three blocks. Further details of the experiment can be found in Peyrard et al. (2016) and Plaza-Bonilla et al. (2015). We focused on N_2O emissions data obtained during the 2010 to 2014 period under 12 winter wheat and faba bean (*Vicia faba* L.) phases of the rotation. These crops are representative of the production under Mediterranean dryland conditions (i.e. winter growing cycle) (López-Bellido et al., 1992; Loss and Siddique, 1994). For each crop, the daily N_2O emissions observation period covered the entire growing season, from sowing until harvest, except in 2012 when the measurements were stopped after the top-dressing fertilization of wheat (Table 2). Crop management practices carried out during the experimental period during the observed growing seasons are reported in Tables S1 and S2 (Supplementary material). N_2O emission data for each crop cycle were obtained from a set of three automatic chambers (0.70 x 0.70 m) inserted into the soil to a depth of 5-10 cm. Four times a day (i.e. each 6-hr) N_2O concentration in the headspace of each chamber was quantified over a 20 min period with a 10 s time step. Fluxes at the time of chamber closure were calculated from the initial increase of the concentration vs. time, using a linear or exponential model fit. A linear model was used if the rate constant of the exponential model was lower than 0.01 min^{-1} or the quality of fit of the exponential was not better than that of the linear ($RMSE_{exp}/RMSE_{lin} > 0.975$) (Peyrard et al. 2016). Daily emissions were then calculated from the average of the 4 fluxes measured per day. The soil temperature at 10 cm depth was monitored with the use of two T107 soil probes (Campbell Scientific Inc, Logan, UT, USA). Monthly soil samplings were carried out at the 0-15 and 15-30 cm soil layers to quantify soil water and mineral N contents. A continuous flow autoanalyzer (Skalar 5100, Skalar Analytic, Erkelenz, Germany) was used for mineral N quantification (NH_4^+ and NO_3^-) after 1 M KCl extraction. Values were transformed to a gravimetric basis using soil bulk density, which was quantified at the beginning and at the end of each N_2O measurement period (i.e. at sowing and crop harvest) by taking two replicate samples of the 0-15 and 15-30 cm soil depths using a 500 cm^3 metal cylinder.

Climatic data (i.e. maximum and minimum air temperatures, global radiation, rainfall, wind, vapor pressure and Penman evapotranspiration) and soil characteristics of each plot (i.e. soil depth, clay proportion, organic N, C:N ratio, $CaCO_3$, pH, albedo, bulk density, water content at field capacity and permanent wilting point) were used to run the STICS model. The average of soil bulk density values at sowing and at harvest was used for the simulations. Five soil layers were considered for simulations: 0-15, 15-30, 30-60, 60-90 and 90-120 cm. The ploughed layer was divided into two layers (0-15 and 15-30 cm) given its key importance for the nitrification and denitrification processes and its consistency with soil layers used for measurements. The model was run without changing the standard parameters controlling the soil physical and biological processes, except the potential rate of N_2O emission from denitrification and threshold WFPS for the onset of denitrification which were modified to improve the quality of fit at Auzeville. They were set at 2.0 kg NO_3^--N ha^{-1} d^{-1} over 0-20 cm and 50%, respectively. Because of the limited availability of measured data on the two other sites and the proximity of these values to the default ones, these parameters were kept constant for all the three sites considered in the study. Simulated and observed N_2O cumulative emissions were compared and the r^2 value, the efficiency of the model (EF), the relative root mean square error (rRMSE) and the mean difference (MD) were calculated according to Eq. S1 (Supplementary material).

2.3. Simulation scenarios

The choice of the simulation scenarios aimed at meeting the requirements of the Mediterranean conditions of the transect: (i) the preponderance of cereals in the rotations given their adaptation to water scarcity (López-Bellido, 1992; Álvaro-Fuentes et al., 2009); (ii) the sole use of winter cash crops, since summer crops would rely on irrigation in the sites with highest water deficit (i.e. HWD-Senés and MDW-Selvanera) and cover crops can result in competition for water with cash crops in dryland semiarid areas (Vigil and Nielsen, 1998; Unger and Vigil, 1998); and (iii) the use of tillage, given the low degree of adoption of no-till techniques in the area of the site with the lowest water deficit (LWD-Auzeville) (DRAAF, 2014). Soil characteristics (Table 1) and the 2005-2014 climatic data obtained at or close to each site (Fig. 1) were introduced as model inputs. In order to compare between sites, the same values of bulk density were taken for the three sites: 1.4 g cm^{-3} for the 0-15 and 15-30 cm soil depths and 1.5 g cm^{-3} for the soil horizons below 30 cm depth, close to actual observed values.

The capacity of different management practices to mitigate N_2O emissions were tested by simulating scenarios differing in: (i) form of N fertilizer (ammonium nitrate AN, calcium nitrate CN, or urea), (ii) rotation, either three cycles of a 3-yr winter cereal rotation (wheat-wheat-barley, called Cer) or three cycles of a mixed rotation (winter pea-wheat-barley, called CerLeg) reducing synthetic N dependence, and (iii) crop residue management (incorporated or removed residues).

A simulation of 9 growing seasons was chosen to (i) represent the climatic variability of the Mediterranean conditions, and (ii) to take into account the carry over effect of the preceding crop of the rotations. Moreover, all the phases of each rotation were simulated each year to take into account the climate x crop interaction. Thus, when not specifically mentioned in the text, annual values correspond to the mean of the three phases. Simulated management practices for the different crops are described in Table 3. For N fertilizer applications, different rates were used on each site according to their yield potential (Table 3). In the rotation including winter pea, N fertilizer applied to the succeeding wheat crop was reduced by 55 kg N ha^{-1} for LWD-Auzeville, taking into account the values measured in the experiment (Plaza-Bonilla et al., 2015). For MWD-Selvanera and HWD-Senés sites a reduction of 35 and 10 kg N ha^{-1} was considered according to the site-specific potential yield compared to LWD-Auzeville. The model was run continuously, i.e. without re-initialization, for each scenario (i.e. from 2006 to 2014). Simulated wheat yield was used as an agronomical indicator of productivity.

The results of the simulation of scenarios were statistically analyzed using the JMP 11 Pro statistical package (SAS Institute Inc, 2014). Normality of data was tested using the W test of Shapiro-Wilk and non-normal data were log-transformed when needed before analysis. Analysis of variance was used to detect significant differences between sites, or management practices or the interaction between the two. When significant, differences were identified at the 0.05 probability level of significance using the Tukey test. N_2O emissions and crop yields were defined as the dependent variables. The site effect mainly represented the precipitation gradient influence. Fertilizer, crop rotation and crop residue management type effects represented management options. The year effect represented the influence of interannual climatic variability. Finally, the interactions (especially site-management practice) allowed detecting the dependence of a management option on the climatic context.

3. Results

3.1. STICS model performance

The STICS model performed quite well at simulating the different N_2O-driving variables in the LWD experiment, consistently with previous results obtained for similar cropping systems (Plaza-Bonilla et al., 2015). Soil temperature and soil moisture dynamics (0-15 cm) were generally well reproduced, as illustrated by results from the 2010-11 faba bean (Fig. 2a and 2b) and the 2013-14 durum wheat (Fig. 3a and 3b) growing seasons. The simulation of soil nitrate performed generally better for the durum wheat, especially after the application of N fertilizer, than for faba bean, as shown in Fig. 3c. For example soil nitrate (0-15 cm depth) was simulated correctly during winter months (from January to March 2011, Fig. 2c), while the model failed at simulating correctly the decrease in nitrate content during the period of active growth of faba bean (from April to June 2011). However, observed and simulated values were close during the bare fallow period after harvest, being 9.7 and 15.9 in August, 19.3 and 15.2 in September and 29.7 and 33.8 kg NO_3^--N ha^{-1} in October, respectively. Soil ammonium (0-15 cm) was simulated acceptably for both crops, for a range of low values (i.e. from 1.4 to 4.8 kg NH_4^+-N ha^{-1}) in the non-fertilized grain legume and a greater one (i.e. from 0.2 to 28.3 kg NH_4^+-N ha^{-1}) after the AN applications in durum wheat (Fig. 2d and 3d, respectively).

The average values of cumulative emissions during the 12 growing seasons were 0.71 and 0.82 kg N_2O-N ha^{-1} for observed and simulated fluxes, respectively. The coefficient of variation (CV) of observed values for each growing season (n = 3) varied between 6 and 37%, which is in the low range of values reported in the literature for N_2O measurements. Observed cumulative N_2O-N ranged between 0.28 and 1.44 kg ha^{-1} while simulated fluxes ranged between 0.46 and 1.72 kg ha^{-1} (Fig. 4). The r^2, EF, rRMSE and MD of the comparison between the cumulative observed and simulated N_2O-N emissions were 0.40, 0.24, 45.6% and 0.1 kg N_2O-N ha^{-1}, respectively.

Overall, simulated N_2O emissions were rather low. However, the ability of the model to reproduce the N_2O dynamics was acceptable. For instance, the mean observed and simulated N_2O-N flux was 2.48 and 3.0 g ha^{-1} d^{-1} for the faba bean growing season of 2011, and 4.46 and 3.66 g ha^{-1} d^{-1} for the durum wheat growing season of 2014, which represents a +21% and -18% difference between observed and simulated values. Similar magnitudes were found between observed and simulated of N_2O fluxes in the faba bean growing season (Fig. 2e). In that example, observed data exceeded simulated ones only during some days in March, with high variability between chambers. However, differences were less than one order of magnitude in all cases. During the wheat crop, the observed and simulated N_2O fluxes varied similarly in most cases (Fig. 3e). The increase in the emissions after wheat top-dressing N fertilization was captured by the model, although there was a tendency to overestimate N_2O peaks (Fig. 3e). Difficulties appeared in simulating late emissions occurring far from N fertilization events. However, the dynamics of observed and simulated cumulative N_2O-N emissions was similar in both crops (Fig. 2f and Fig. 3f).

3.2. Precipitations and crop yields simulated in scenarios

Precipitation values and their distribution over the nine growing seasons used for the simulations (i.e. from 2006 to 2014) presented large differences between sites (Fig. 1). During these 9 growing seasons (i.e. defined as the period from July to June of the subsequent year) precipitation varied between 166 and 434 mm, 315 and 559 mm and 516 and 823 mm in HWD-Senés, MWD-Selvanera and LWD-Auzeville, with average values of 303, 460 and 637 mm, respectively (Figs. 1a, 1b and 1c). The CV of annual precipitation was high and similar between sites: 23, 15 and 18% for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively. A decrease in the duration of water deficit occurs in the south-to-north direction of the transect:

monthly water deficit (calculated as PET – precipitation) exceeded 100 mm during the May-to-August, June-to-August and July-to-August periods in the HWD, MWD and LWD sites, respectively. The frequency of daily rainfall events ≥ 30 mm increased from the south-to-north direction with 9, 12 and 14 days for the HWD, MWD and LWD sites, respectively.

Simulated grain yield was significantly affected by water deficit, with significant differences between sites on wheat production, with higher yields when decreasing water deficit (Table S3, Supplementary material; Fig. 5b), a trend that was also observed in barley and winter pea (Fig. 5c and 5d). Simulated yields of winter pea showed an increase according to the potential of each site with an average of 0.5, 1.7 and 3.9 Mg ha^{-1} for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively. Cereals showed larger simulated productions, with an average of 1.1, 4.1 and 7.5 Mg ha^{-1}. In MWD-Selvanera, the scenario with the incorporation of winter pea in the rotation, the production of wheat increased significantly by 15%. In the two other sites, HWD-Senés and LWD-Auzeville, there was no significant difference in wheat production between rotations. The yields simulated by the STICS model were sensitive to the climatic conditions of the year (Fig. 5b, 5c and 5d).

3.3. Cumulative N_2O emissions simulated in scenarios

The effect of the different factors on N_2O cumulative emissions is presented at Table S3 (Supplementary material). Site, and thus climatic gradient, had a strong effect on the production of N_2O from nitrification and denitrification and total N_2O emissions, with an increase from high to low water deficit. As an average of all the scenarios taken into account, cumulative N_2O losses were 0.26, 0.65 and 2.51 kg N_2O-N ha^{-1} yr^{-1} for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively (Table 4). However, the contribution of denitrification to total N_2O emissions did not follow the same relationship, being largest in LWD-Auzeville and smallest in MWD-Selvenera with intermediate values in HWD-Senés.

Most of the management scenarios simulated, when analyzed as single effects, significantly affected the cumulative N_2O emissions and/or the N_2O producing processes (i.e. nitrification and denitrification) and the relative contribution of the denitrification to total N_2O emission (Table S3, Supplementary material). The type of N fertilizer affected total N_2O losses, with higher N losses (+6 and +8%) for urea compared to AN or CN. This effect was mainly associated to an increase in N_2O produced through the nitrification process. As a consequence, the relative importance of denitrification on N_2O losses was also impacted by the nature of the fertilizer. The effect of fertilizer form on total N_2O emissions was not site (or climate) dependent as shown by the lack of interaction between site and fertilizer type.

On the contrary, the effect of the other management options depended on the site of study and thus the climate gradient. The type of rotation had no significant effect on total N_2O emissions although it significantly affected the amount of N_2O derived from nitrification which was slightly larger for the rotation based on cereals than that with winter pea (Table 4). The site x rotation interaction was however significant: in HWD-Senés, the Cer rotation showed larger total N_2O losses due to a larger contribution from both nitrification and denitrification processes when compared to the rotation including a grain legume (CerLeg). Crop residue management significantly affected total N_2O losses irrespective of the site, but the presence of an interaction with the site indicates that its effect was dependent on the climatic context: it was larger in the wetter sites, e.g. 20% higher in LWD-Auzeville when returning crop residues compared to their removal. This was due to a larger contribution of both nitrification and denitrification processes (11 and 22% increase, respectively). The climate x residue management interaction is also illustrated by the exponential relationship between N_2O losses and soil water accumulation during the growing season (Fig. 6).

A significant interaction between rotation and N fertilization type was found (Table S3, Supplementary material). N_2O emissions did not differ between fertilizer types in the CerLeg rotation, whereas in the Cer rotation larger total and nitrification-driven N_2O emissions occurred with urea as fertilizer (Table 4). In the Cer rotation, the relative proportion of N_2O resulting from denitrification decreased in the order CN > AN > urea. A significant interaction was found between residue management and N fertilizer form on total and nitrification-driven emissions: N_2O emissions were not affected by the fertilizer form when returning crop residues, but were elevated with urea fertilization in combination with crop residue removal.

Finally, the year had a strong effect on N_2O emissions, both as main effect and through interaction with other factors. This is a clear indication of the strong influence of precipitation variability which is analyzed in the next section.

3.4. N_2O emissions affected by precipitation variability

Simulated N_2O fluxes were highly sensitive to the annual climatic conditions as shown by i) the role played by rainfall between sites (Fig. 6) and between years for a given site (Fig. 5a), ii) the significance of the year single effect and its interactions with the rest of effects tested (Table S3, Supplementary material). The inter-annual variability (represented by the CV) of N_2O emissions averaged over the scenarios simulated with STICS reached 52, 49 and 27% for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively. Despite a lower CV, Auzeville site exhibited important inter-annual variation of N_2O fluxes and cumulative emissions ranged from 1 to almost 4 kg N_2O-N ha^{-1} y^{-1} (Fig 6a). Another example of the influence of precipitation variability is found at MWD-Selvanera in 2014 in the barley-pea-wheat sequence (BPW, CerLeg rotation). The wheat following winter pea resulted in a cumulative N_2O emission of 2.79 kg N_2O-N ha^{-1} yr^{-1}, which is much larger than the average of the rest of the years (2006-2013) of the same sequence (0.61 kg N_2O-N ha^{-1} yr^{-1}) and the 2014 value of the pea-wheat-barley (PWB) and wheat-barley-pea (WBP) sequences (0.79 and 0.94 kg N_2O-N ha^{-1} yr^{-1}, respectively). Cumulative N_2O emissions in the 2009-2010 growing season in LWD-Senés were also much lower than in the rest of the years due to the dry conditions from June to September 2009 (Fig. 1a). For a given site and management scenario, the dynamic features of N_2O emissions were also highly sensitive to the conditions of the year considered, with increases in the cumulative N_2O emissions after N fertilizer applications (Fig. 7a-l) or incorporation of low C:N ratio winter pea residues in soil (e.g. 2009-2010 season in Fig. 7g-l) which was exacerbated under wet soil conditions.

The interaction between year and management options was always significant, which indicates that the potential of mitigation associated to a practice is strongly dependent on the climate of the year considered. For instance, during the 2006 to 2014 period, cumulative N_2O emissions for the Cer rotation varied between 0.13 and 0.66, 0.26 and 0.97 and 1.03 and 3.67 kg N_2O-N ha^{-1} yr^{-1} for HWD-Senés, MWD-Selvanera and LWD-Auzeville, respectively; in the CerLeg rotation, the emissions ranged between 0.12-0.51, 0.20-1.51 and 1.93-3.21 kg N_2O-N ha^{-1} yr^{-1}, respectively.

4. Discussion

4.1.Rainfall variability, crop yields and N_2O emissions

Tier 1 methodology proposed by the IPCC (2006) does not take into account explicitly pedoclimatic and agricultural management influences on N_2O emissions. The results of the present work highlight the potential large variability of N_2O emissions under Mediterranean conditions, both along an aridity gradient and from year to year. As a consequence, the use of models (i.e. Tier 3) seems especially relevant in the Mediterranean context for a more precise quantification of N_2O emissions taking into account its typical strong variability (Conen et al., 2000).

The ability of the STICS model to simulate N_2O emissions was first evaluated using data observed in the LWD-Auzeville for which daily measurements were available. The test indicated a reasonably consistency between observed and simulated cumulative values which varied between 0.28-1.44 and 0.46-1.71 kg N_2O-N ha^{-1} yr^{-1}, respectively. The mean cumulative

N_2O emissions predicted by the STICS model in the two other sites, HWD-Senés and MWD-Selvanera, were 0.26 and 0.65 kg N_2O-N ha^{-1} yr^{-1}, which falls in the range of published values for semiarid dryland Mediterranean conditions. For instance, Plaza-Bonilla et al. (2014a) measured the effect of different tillage and N fertilizer management practices on N_2O emissions in one experimental site close to HWD-Senés and another slightly drier than MWD-Selvanera (i.e. with an annual water deficit of 425 mm compared to the 350 mm of the MWD site), both under winter cereal production in dryland conditions. In the site close to HWD-Senés, they measured an emission of 0.16, 0.21 and 0.58 kg N_2O-N ha^{-1} for three rates of fertilizer (0, 75 and 150 kg N ha^{-1}) as ammonium sulphate and AN under conventional tillage (i.e. disk plough and chisel). In the site drier than MWD-Selvanera, the emission was 0.08, 0.41 and 0.38 kg N_2O-N ha^{-1} yr^{-1} when applying 0, 60 and 120 kg N ha^{-1} as ammonium sulphate and AN with a full inversion tillage based on moldboard ploughing. Similar magnitudes were measured in a semiarid area in Central Spain with 315 mm of annual water deficit (calculated as ETo minus precipitation); cumulative N_2O emissions of 0.35 kg N ha^{-1} during a spring barley growing season (i.e. from January to June) fertilized with urea were reported (Meijide et al., 2009). At the same site, Ábalos et al. (2013) measured the N_2O emissions under a rainfed barley crop. They found a cumulative emission of 0.67 and 1.30 kg N_2O-N ha^{-1}, respectively, after removing or incorporating the previous corn residues, during the period from the incorporation of residues to the harvest (i.e. mid-November to end of June). A similar range of emission (0.32-0.68 kg N_2O-N ha^{-1} yr^{-1}) was reported by Kessavalou et al. (1998) in the semiarid High Plains of the USA in a wheat-fallow rotation. This range is consistent with that obtained in the simulations, which broadens the confidence in simulated results despite the usual difficulties in simulating the dynamics of N_2O emissions.

As pointed out before, the significant interannual variability of rainfall had a clear influence on cumulative N_2O emissions simulated by the model in the three sites analyzed. In temperate semiarid areas and at the landscape scale, fluctuation of N_2O emission is mainly influenced by precipitation and irrigation, and when soil moisture is favorable, soil mineral N, temperature and labile C availability become important (Corre et al., 1996; Rowlings et al., 2015). The CV of the simulated cumulative N_2O emissions reached 52, 49 and 27% for HWD-Senés, MWD-Selvanera and LWD-Auzeville respectively, showing the strong interannual variability of N_2O fluxes in the Mediterranean conditions. Similar high interannual variability was reported in the few multiyear greenhouse gas datasets published in the literature. In the site equivalent to HWD-Senés, Plaza-Bonilla et al. (2014a) found a CV of 20% for cumulative emissions measured over two seasons (2011-13) and five fertilization treatments. Du et al. (2006) reported an interannual CV of 71% when measuring N_2O emissions in a cold semi-arid grassland in inner Mongolia.

The STICS model predicted that water deficit exerted a large impact on crop yields, with a winter cereal yield varying between 0.5 and 9.5 Mg ha^{-1} along the transect. Such a variation is commonly observed under Mediterranean conditions depending on the amount of water available for the crop (Cantero-Martínez et al., 2003, 2007). Plaza-Bonilla et al. (2014b) compared three sites with different yield potentials along the semiarid Ebro valley (NE Spain). They found that winter cereal production ranged from 0.4 to 8.2 Mg ha^{-1} in the 2009-10 growing season. Simulated winter pea yields were very low in HWD-Senés, between 0.1 and 1.4 Mg ha^{-1}, demonstrating the probability of crop failure and associated economic risk when establishing grain legumes in the most extreme locations under Mediterranean conditions, as reported by Álvaro-Fuentes et al. (2009).

4.2. Management scenarios for N_2O mitigation

We compared the potential to reduce N_2O emissions in Mediterranean dryland field crops production by different scenarios of management practices. All driving variables (i.e. proportion of O_2 in the soil pores, temperature, mineral N and labile C) were directly affected by agricultural management practices (e.g. N fertilization, crop residues incorporation, soil management, etc.), in interaction with the soil water status. The simulations carried out showed the sensitivity of N_2O emissions to the nature of the fertilizer used (including substitution of legumes in the rotation instead of mineral N fertilizer) and residue management, effects well documented in the existing literature (e.g. Bouwman et al., 2002; Ábalos et al., 2013).

The introduction of one winter grain legume (i.e. winter pea) in the traditional cereal-based rotations reduced significantly the emissions of N_2O only in the driest site (HWD-Senés), given the low amount of winter pea residues produced susceptible of being decomposed during the successive phase of the rotation (i.e. wheat phase). In LWD-Auzeville and MWD-Selvanera, the reduction of N_2O emissions simulated as a result of the N fertilizer savings in durum wheat preceded by winter pea, was offset by an increase in emissions due to the decomposition of the crop residues from the winter pea crop. The simulated N_2O emissions during the wheat phase preceded by winter pea in the CerLeg rotation were 35 and 48% larger than the corresponding wheat phase of the Cer rotation in MWD-Selvanera and LWD-Senés, respectively. In a recent meta-analysis, Basche et al. (2014) reported that the incorporation of legume cover crop residues to the soil increased N_2O emissions when compared to the incorporation of cereal crop residues with a larger C:N ratio. The incorporation of low C:N ratio residues to the soil usually increases net N mineralization contributing to higher nitrate availability, and concomitantly to larger N_2O emissions (Firestone and Davidson, 1989).

Contradictory results were obtained by De Antoni-Migliorati et al., (2015) when using the DayCent model in a simulation study carried out in irrigated Oxisols under subtropical conditions. The authors tested the interest of introducing legume pastures in summer cereal-based (i.e. sorghum) cropping systems. They simulated a reduction in N_2O emissions when introducing legume pastures and lowering sorghum N-fertilization by 30%. However, under those subtropical conditions sorghum is planted right after the incorporation of the legume, improving the synchrony between crop demand and N availability due to legume residues decomposition, reducing the susceptibility to N_2O emissions. Unfortunately, under dryland Mediterranean conditions, the establishment of two crops per year (i.e. a cash and cover crop succession or a double cropping) is impeded by water scarcity, being only possible in the wettest sites and/or with irrigation. As a consequence, N_2O emissions associated to residue decomposition and mineral N release can occur during the fallow period between grain legume harvest (i.e. June) and subsequent crop sowing (i.e. November) as already observed at the LWD site (Peyrard et al. 2016). However, Barton et al. (2014) suggested that it is unlikely that grain legume cropping would increase soil N_2O emissions in semi-arid conditions. These contradictory findings suggest the need to carry out more field-based measurements of N_2O emissions under semi-arid conditions when diversifying cereal-based cropping systems, which could be designed with the help of model simulations.

According to our simulations, the removal of crop residues would reduce the emissions of N_2O by 0.45 kg N_2O-N ha^{-1} yr^{-1} in LWD-Auzeville, the most productive site. After compiling studies carried out in eastern Canada and northeastern US, Gregorich et al. (2005) reported larger N_2O emissions when incorporating stubble residues in soil instead of leaving crop residues on the soil surface: 2.41 vs. 1.19 kg N_2O-N ha^{-1} yr^{-1}. Abalos et al. (2013) also found a marked increase (+105%) in N_2O emissions when incorporating maize stover in a non-irrigated barley crop compared to crop residues removal. They attributed the increase to a larger amount of dissolved organic carbon, nitrate availability and more anaerobic microsites enhancing denitrification due to the maize stover. However, the removal of crop residues represents a significant loss of soil organic carbon and soil quality which could counteract the lower N_2O emissions and increase the C footprint of the system. The input of C to the soil as crop residues is of a paramount importance to maintain the stock of soil organic C under dryland conditions (Plaza-Bonilla et al., 2016). Taking into account a GWP of 265 (IPCC,

2013) the emission of 0.45 kg N_2O-N ha^{-1} yr^{-1} would be equivalent to the sequestration of 50 kg C ha^{-1} yr^{-1} in the soil, a value of C sequestration which can be reached under dryland conditions when returning the crop residues to the soil (Lal, 2004).

Given its lower price, urea is one of the most commonly used nitrogenous fertilizers by farmers in the Mediterranean basin (FAOSTAT; Ryan et al., 2009). However, the simulation predicted an increase in N_2O emissions when applying urea compared to ammonium nitrate, due to greater losses of N_2O by nitrification. Decock (2014) analyzed data collected in corn cropping systems of the Midwestern US and South-East Canada and found a tendency of larger N_2O emission for ammonium nitrate than for urea. However, she pointed out that fertilizer N-forms different from nitrate would enhance N_2O emissions in dry conditions that favor nitrification. Urea can also lead to larger NH_3 losses to the atmosphere than other N fertilizers, particularly in the Mediterranean region where soils are commonly basic (Sanz-Cobena et al., 2008; Ryan et al., 2009). One technological option for the reduction of N_2O losses from synthetic fertilizers is the use of nitrification inhibitors. Although it has received much attention, such chemicals are unlikely to be used extensively, due to its high cost and the low productivity of field crops under dryland Mediterranean conditions (Ryan et al., 2009).

5. Conclusions

Results from this simulation work indicate that N_2O emissions from rainfed field crop production in a water deficit transect, range from 0.3 to 2.5 kg N_2O-N ha^{-1} yr^{-1}, covering a large panel of agricultural dryland production under Mediterranean conditions. The lower N_2O emissions in the driest sites were not only related to lower N fertilization rates but also to other factors associated with the Mediterranean characteristics, particularly, the dryer water regime. The interannual variability of rainfall, which is an intrinsic characteristic of the Mediterranean climate, strongly influenced the simulated emissions of N_2O during the 9-yr period considered, with an inter-annual variability ranging between 27 and 52% (depending on the site). Thus, when designing experiments, emission measurements over at least a complete rotation and/or several years should be favored. Simulated seasonal N_2O emissions were driven by N fertilization events and low C:N ratio of crop residues (i.e. legumes) decomposing after harvest.

All management options aiming at soil N_2O emissions mitigation were affected by climate. According to the model, the application of urea would increase N_2O emissions when compared to other fertilizers partially or totally based on nitrate. This effect was observed in all cases but its intensity varies with the water deficit gradient. This model output, which remains to be demonstrated experimentally, can be explained by winter crops growing in the specific conditions of the Mediterranean climate, which favor nitrification N_2O losses. The introduction of winter pea in the traditional cereal-based rotation only reduced N_2O emissions in the driest site. In the sites with greater yield potential, the decomposition of pea residues (with low C:N ratio) could have counteracted the N_2O emissions associated with the reduction in N fertilizer applied to the succeeding crop. Crop residue removal reduced N_2O emissions in the most productive site with the lowest water deficit, i.e. LWD-Auzeville. However, reducing crop residues return to soil could lead to soil carbon losses which is negative both for the overall C footprint of the system, soil quality and future yields. Our work demonstrates the usefulness of modelling approaches combined with experimental data, to take into account climatic variability and explore how the efficiency of mitigation practices is affected by the agro-pedo-climatic conditions.

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Figure captions

Fig. 1 Mean monthly precipitation (black columns) and potential evapotranspiration temperature (PET, red columns) at each site: a) HWD-Senés, b) MWD-Selvanera and c) LWD-Auzeville (HWD, MWD and LWD, high, medium and low water deficit, respectively) 30-yr average values (in italics) and 2005 to 2014 growing seasons (i.e. shown from July to June). For each site and growing season mean precipitation is reported within the sub-figures.

Fig. 2 Observed and simulated soil temperature (a), water content (b), nitrate content (c) and ammonium content (d) in the 0-15 cm soil layer, daily N_2O fluxes (e) and cumulative N_2O losses (f) during a faba bean growing season in 2011 in LWD-Auzeville. Vertical bars correspond to the standard deviations.

Fig. 3 Observed and simulated soil temperature (a), water content (b), nitrate content (c) and ammonium content (d) in the 0-15 cm soil layer, daily N_2O fluxes (e) and cumulative N_2O losses (f) during a durum wheat growing season in 2014 in LWD-Auzeville. Vertical bars correspond to the standard deviations. Vertical arrows indicate the applications of ammonium nitrate fertilizer.

Fig. 4 Observed and simulated cumulative N_2O emissions of different cropping seasons (10-11, 11-12, 12-13 and 13-14) of faba bean (FB) and durum wheat (DW) crops in LWD-Auzeville. Horizontal bars indicate the standard deviations of measurements (n = 3). The previous cover crops (bc, berseem clover, oat, vetch+mu, vetch and mustard mixture) and bare fallow (bf) phases are shown in brackets.

Fig. 5. Simulated annual N_2O emissions (a), and wheat, barley and winter pea grain yield (b, c and d, respectively) in each site versus rotation type (Cer ,or CerLeg) and crop sequence

(WWB, WBW, BWW and PWB, WBP, BPW) during the 2006-2014 period. Values are the mean of the three fertilizer types and the two crop residues managements.

Fig. 6 Relationship between annual N_2O emissions (simulated) and a water availability indicator (soil water content at the beginning of soil water recharge period (July) + annual rainfall). Two exponential relationships were fitted, depending on crop residues management (incorporated vs. removed). Values are the mean of two rotation types and three N fertilizer types. HWD, MWD and LWD correspond to high (Senés), medium (Selvanera) and low (Auzeville) water deficit sites.

Fig. 7 Simulated cumulative N_2O emissions in a cereal (a-f) and cereal-legume rotation (g-l) with three N fertilizer (AN, ammonium nitrate, CN, calcium nitrate and Urea) and two crop residues management (No residues, residues removed; Residues, residues incorporated) scenarios during the 2006-2014 period at each site. The wheat-W/wheat-W/barley-B and the winter pea-P/wheat-W/barley-B sequences of the Cer and CerLeg rotations are shown. Arrows indicate the first N fertilizer application on each crop and the incorporation of pea residues to the soil. (For interpretation of the legend the reader is referred to the web version of this article.)

Table 1. Site and general soil characteristics in the 0–30 cm soil depth of the three experimental sites. HWD, MWD and LWD indicate high, medium and low water deficit, respectively. PET = potential evapotranspiration.

	Site		
	Senés (HWD)	Selvanera (MWD)	Auzeville (LWD)
Country/Region	Spain/Aragón	Spain/Catalonia	France/Midi-Pyrénées
Latitude	41º 54' N	41º 49' N	43º 31' N
Longitude	0º 30' W	1º 17' E	1º 30' E
Elevation (m)	395	470	150
Annual precipitation (mm)	327	450	685
Annual PET (mm)	1197	800	905
Annual water deficit (mm)[a]	870	350	220
Soil classification[b]	Typic Calcixerept	Fluventic Xerochrept	Typic Hapludalf
pH	8.0	8.3	7.0
Soil organic carbon (g kg^{-1})	15.6	10.5	8.7
$EC_{1:5}$ (dS m^{-1})	1.04	0.16	0.0
CaCO3 eq. (%)	29.5	35.0	0.3
Water retention (% vol.) at			
-33 kPa	26.8	27.3	30.7
-1500 kPa	13.9	12.1	12.8
Particle size distribution (%)			
Sand (2,000-50 μm)	6.2	36.5	37.6
Silt (50-2 μm)	63.3	46.4	36.8
Clay (2 μm)	30.5	17.1	25.6
Rooting depth (m)	0.6-0.9	0.9-1.0	1.2

[a] Calculated as the difference between annual precipitation and annual evapotranspiration.

[b] According to the USDA classification (Soil Survey Staff, 2014).

Table 2. Summary of the growing seasons and duration of the daily N_2O emission measurements used to test the model in the durum wheat and faba bean phases (in bold) depending on the rotation carried out in Auzeville (SW France).

Rotation	Crop analyzed	Growing season	N_2O measurements	
			Beginning	End
SR* – (bf) – SF – (bf) – **DW** – (bf)	Durum wheat	2010-11	12/10/2010	06/26/2011
	Durum wheat	2012-13	11/21/2012	07/13/2013
SR – (vol.) – SF – (bc) – **DW** – (vetch+phac.)	Durum wheat	2010-11	12/10/2010	06/26/2011
	Durum wheat	2012-13	11/21/2012	07/13/2013
	Durum wheat	2013-14	12/16/2013	06/28/2014
SF – (bf) – **FB** – (bf) – **DW** – (bf)	Faba bean	2010-11	12/16/2010	06/28/2011
	Durum wheat	2010-11	12/16/2010	06/26/2011
	Durum wheat	2011-12	10/17/2011	04/24/2012
SF – (oat) – **FB** – (vetch+mu) – **DW** – (vetch+oat)	Faba bean	2010-11	12/16/2010	06/28/2011
	Durum wheat	2010-11	12/16/2010	06/26/2011
	Durum wheat	2011-12	10/17/2011	04/24/2012
	Durum wheat	2012-13	11/30/2012	06/12/2013

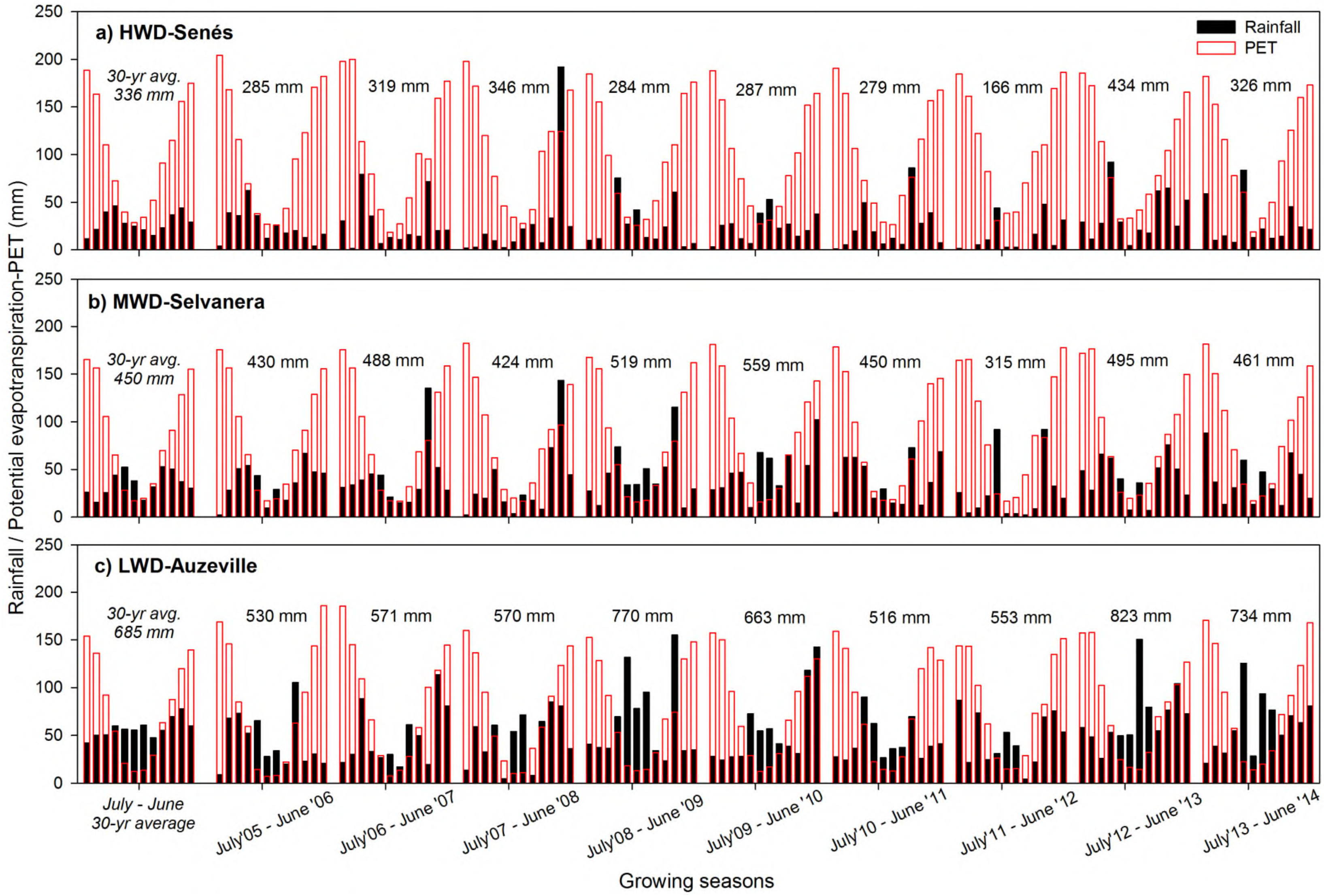
*bc, bf, DW, FB, mu, phac., SF, SR and vol. stand for berseem clover, bare fallow, durum wheat, faba bean, mustard, phacelie, sunflower, sorghum and sorghum volunteers, respectively.

Table 3. Simulated crop management practices carried out in a Mediterranean transect (HWD, MWD and LWD, high, medium and low water deficit, respectively) to analyze the impact of different management scenarios (in italics) (cereal vs. cereal+grain legume rotation, N fertilizer type: urea, AN, ammonium nitrate and CN, calcium nitrate, crop residue management: removed vs. incorporated, and their interactions) on N_2O emissions.

Rotation phase	Management practice	Date	Tillage implement and input type	Nitrogen fertilizer applied (kg N ha^{-1})		
				HWD	MWD	LWD
			Winter cereal rotation (wheat-wheat-barley)			
Wheat	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	1st Nov.	400 seeds m^{-2}.			
	N fertilization	4th and 27th April	*Urea, AN and CN*	60+0	70+40	100+70
	Harvest	1st July	*Crop residues incorporated vs. removed*			
Wheat	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	1st Nov.	400 seeds m^{-2}.			
	N fertilization	4th and 27th April	*Urea, AN and CN*	60+0	70+40	100+70
	Harvest	1st July	*Crop residues incorporated vs. removed*			
Barley	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	15th Nov.	400 seeds m^{-2}.			
	N fertilization	4th and 27th April	*Urea, AN and CN*	50+0	60+30	100+50
	Harvest	1st July	*Crop residues incorporated vs. removed*			
			Winter cereal-legume rotation (winter pea-wheat-barley).			
Winter pea	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	20th Nov.	70 seeds m^{-2}			
	Harvest	1st July	Crop residues incorporated			
Wheat	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	1st Nov.	400 seeds m^{-2}.			
	N fertilization	4th and 27th April	*Urea, AN and CN*	50+0	45+30	65+50
	Harvest	1st July	*Crop residues incorporated vs. removed*			
Barley	Tillage	15th Sept. and 20th Oct.	Disk tandem – Rotary harrow			
	Sowing	15th Nov.	400 seeds m^{-2}.			
	N fertilization	4th and 27th April	*Urea, AN and CN*	50+0	60+30	100+50
	Harvest	1st July	*Crop residues incorporated vs. removed*			

Table 4. Simulated annual N_2O emissions from nitrification and denitrification, total N_2O emissions and N_2O ratio in two rotation types (cereal-based, Cer rot; cereal-legume, CerLeg) with different crop residue management (Res. Rem., residues removed, Res. Incorp., residues incorporated) and N fertilizer types (AN, ammonium-nitrate, CN calcium nitrate, Urea) in three sites. Values correspond to the average of 9 years (2006-2014) and the three phases of each rotation. Different letters indicate significant differences between treatments at P<0.05. std. dev is shown between brackets.

Selected treatments		Nitrification N_2O-N (kg N_2O-N ha^{-1} yr^{-1})	Denitrification N_2O-N (kg N_2O-N ha^{-1} yr^{-1}) (1)	Total N_2O-N (kg N_2O-N ha^{-1} yr^{-1}) (2)	(1):(2)
HWD		0.08 (0.05) c	0.19 (0.14) c	0.26 (0.16) c	0.69 (0.15) b
MWD		0.27 (0.14) b	0.38 (0.31) b	0.65 (0.43) b	0.56 (0.11) c
LWD		0.58 (0.18) a	1.92 (0.80) a	2.51 (0.90) a	0.75 (0.09) a
Cer rot.		0.32 (0.25) a	0.82 (0.90)	1.13 (1.12)	0.67 (0.14)
CerLeg rot.		0.30 (0.24) b	0.84 (0.95)	1.15 (1.16)	0.67 (0.14)
AN		0.31 (0.23) b	0.82 (0.91)	1.13 (1.13) b	0.66 (0.11) b
CN		0.25 (0.22) c	0.85 (0.94)	1.10 (1.13) b	0.73 (0.14) a
Urea		0.37 (0.28) a	0.82 (0.92)	1.19 (1.17) a	0.62 (0.14) c
Res. Rem.		0.30 (0.24) b	0.76 (0.81) b	1.06 (1.02) b	0.67 (0.14)
Res. Incorp.		0.33 (0.61) a	0.90 (1.02) a	1.22 (1.25) a	0.67 (0.14)
HWD	Cer rot.	0.09 (0.05) c	0.21 (0.14) c	0.29 (0.16) c	0.69 (0.15)
	CerLeg rot.	0.07 (0.04) d	0.16 (0.14) d	0.23 (0.16) d	0.69 (0.15)
MWD	Cer rot.	0.27 (0.12) b	0.34 (0.16) b	0.61 (0.25) b	0.56 (0.11)
	CerLeg rot.	0.28 (0.16) b	0.42 (0.40) b	0.70 (0.55) b	0.57 (0.10)
HWD	Cer rot.	0.60 (0.20) a	1.90 (0.80) a	2.50 (0.91) a	0.74 (0.09)
	CerLeg rot.	0.57 (0.16) a	1.95 (0.80) a	2.52 (0.90) a	0.76 (0.08)
HWD	Res. Rem.	0.08 (0.05) d	0.19 (0.15) d	0.27 (0.17) d	0.70 (0.15) b
	Res. Incorp.	0.08 (0.05) d	0.18 (0.13) d	0.26 (0.16) d	0.68 (0.15) b
MWD	Res. Rem.	0.26 (0.14) c	0.36 (0.28) c	0.62 (0.38) c	0.57 (0.10) c
	Res. Incorp.	0.28 (0.15) c	0.40 (0.33) c	0.68 (0.45) c	0.56 (0.11) c
LWD	Res. Rem.	0.55 (0.17) b	1.73 (0.68) b	2.28 (0.77) b	0.74 (0.09) a
	Res. Incorp.	0.61 (0.19) a	2.12 (0.86) a	2.73 (0.97) a	0.76 (0.08) a
Cer rot.	AN	0.32 (0.23) b	0.79 (0.88)	1.11 (1.09) b	0.65 (0.11) c
	CN	0.20 (0.17) d	0.85 (0.94)	1.05 (1.09) b	0.78 (0.10) a
	Urea	0.43 (0.29) a	0.80 (0.89)	1.23 (1.17) a	0.57 (0.12) d
CerLeg rot.	AN	0.31 (0.24) bc	0.84 (0.95)	1.14 (1.16) b	0.66 (0.12) bc
	CN	0.30 (0.25) c	0.84 (0.94)	1.15 (1.17) b	0.68 (0.15) b
	Urea	0.31 (0.25) c	0.85 (0.95)	1.15 (1.17) b	0.67 (0.14) b
Res. Rem.	AN	0.30 (0.22) cd	0.75 (0.80)	1.04 (1.0) bc	0.66 (0.11) c
	CN	0.21 (0.18) e	0.78 (0.82)	0.99 (0.98) c	0.77 (0.11) a
	Urea	0.38 (0.27) a	0.76 (0.82)	1.14 (1.07) ab	0.57 (0.13) d
Res. Incorp.	AN	0.33 (0.25) bc	0.89 (1.01)	1.21 (1.24) a	0.65 (0.12) c
	CN	0.30 (0.25) d	0.91 (1.04)	1.21 (1.25) a	0.69 (0.15) b
	Urea	0.35 (0.29) b	0.89 (1.01)	1.24 (1.26) a	0.65 (0.15) c



a) HWD-Senés
Rainfall
PET
30-yr avg.
336 mm
285 mm
319 mm
346 mm
284 mm
287 mm
279 mm
166 mm
434 mm
326 mm
b) MWD-Selvanera
30-yr avg.
450 mm
430 mm
488 mm
424 mm
519 mm
559 mm
450 mm
315 mm
495 mm
461 mm
c) LWD-Auzeville
30-yr avg.
685 mm
530 mm
571 mm
570 mm
770 mm
663 mm
516 mm
553 mm
823 mm
734 mm
Rainfall / Potential evapotranspiration-PET (mm)
July - June
30-yr average
July'05 - June '06
July'06 - June '07
July'07 - June '08
July'08 - June '09
July'09 - June '10
July'10 - June '11
July'11 - June '12
July'12 - June '13
July'13 - June '14
Growing seasons

Fig. 1

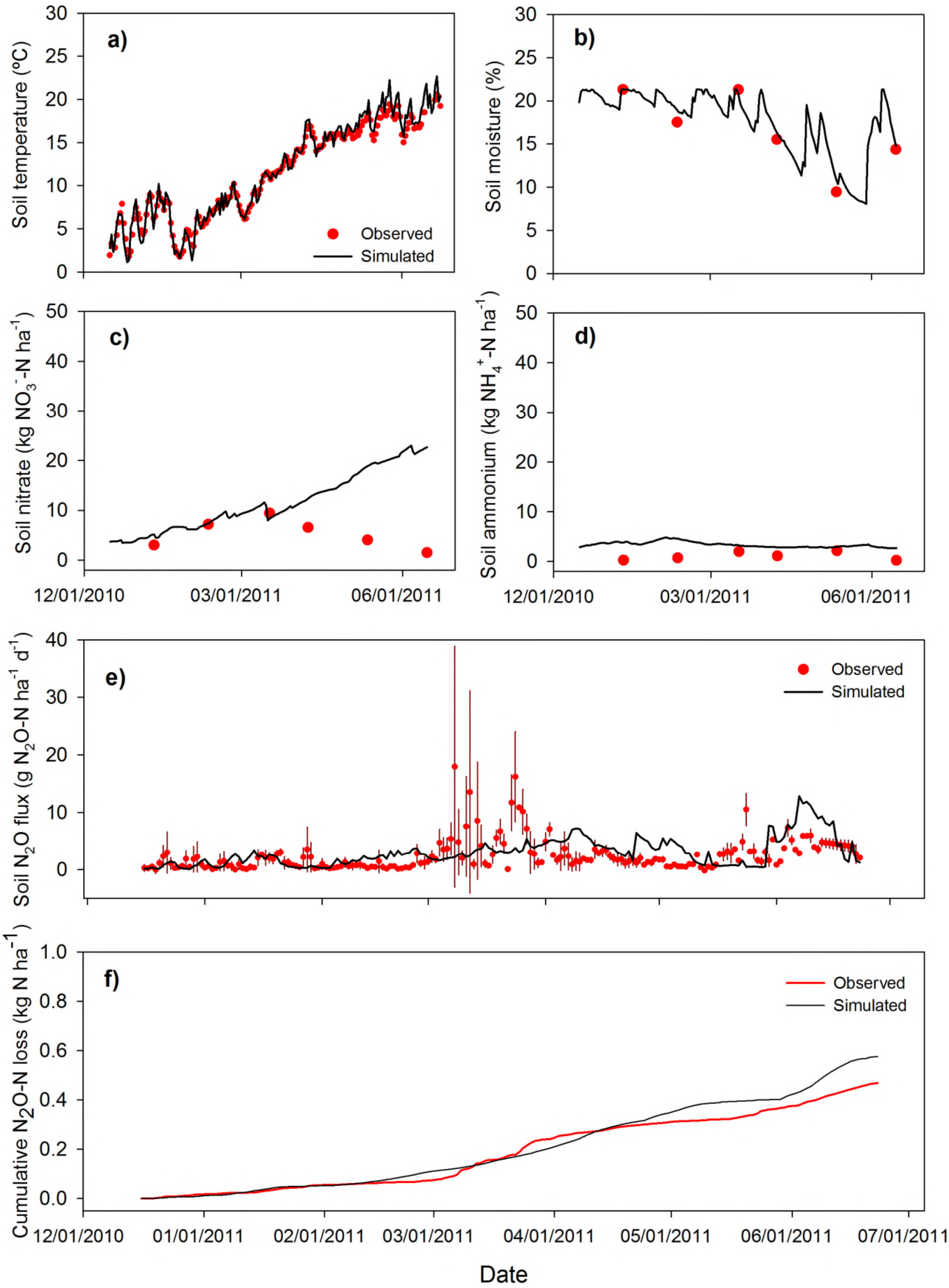

a)
Soil temperature (°C)
Observed
Simulated
b)
Soil moisture (%)
c)
Soil nitrate (kg NO3--N ha-1)
d)
Soil ammonium (kg NH4+-N ha-1)
12/01/2010
03/01/2011
06/01/2011
e)
Soil N2O flux (g N2O-N ha-1 d-1)
Observed
Simulated
f)
Cumulative N2O-N loss (kg N ha-1)
Observed
Simulated
12/01/2010
01/01/2011
02/01/2011
03/01/2011
04/01/2011
05/01/2011
06/01/2011
07/01/2011
Date

Fig. 2

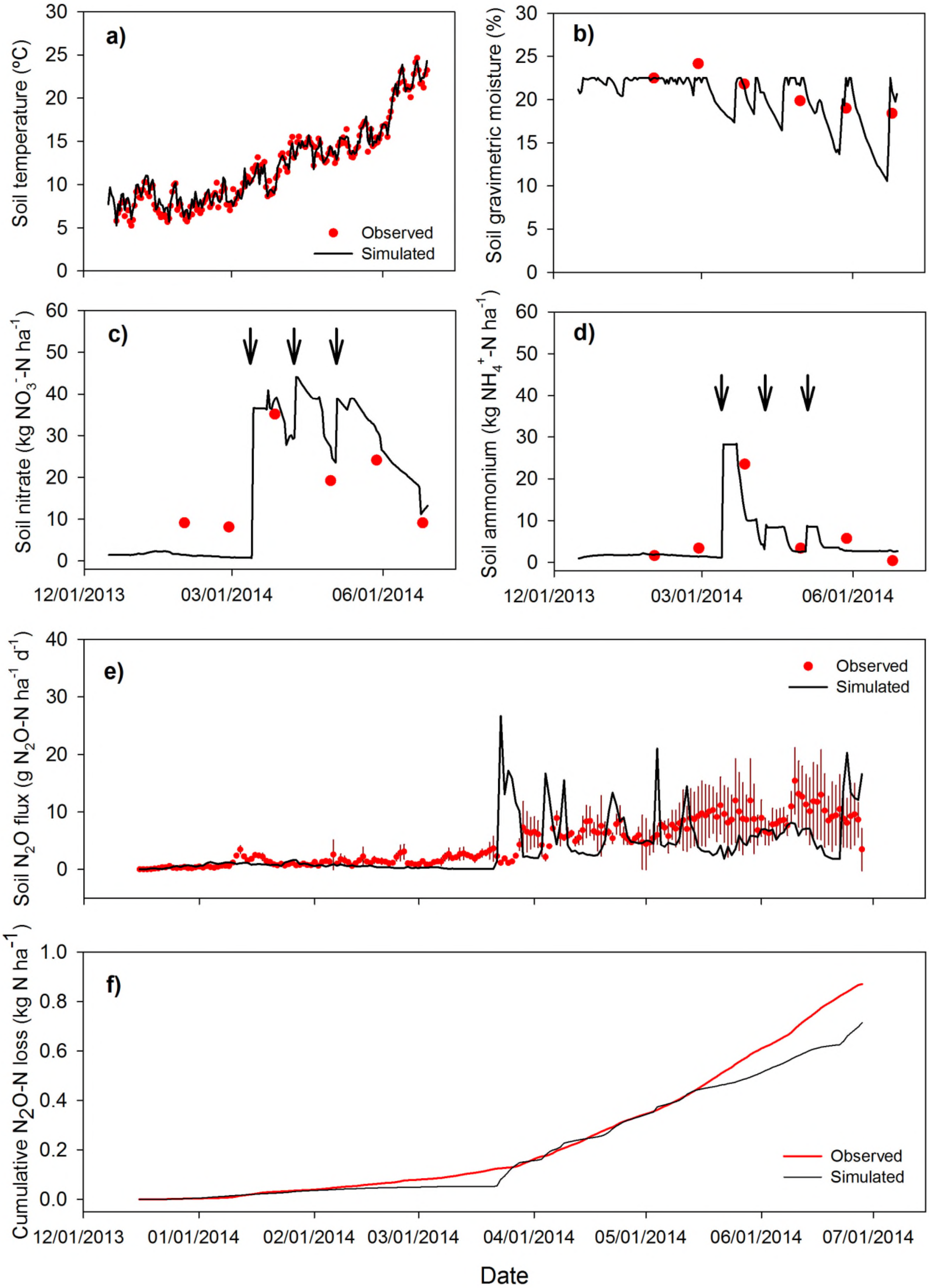

a)
Soil temperature (ºC)
Observed
Simulated
b)
Soil gravimetric moisture (%)
c)
Soil nitrate (kg NO3--N ha-1)
d)
Soil ammonium (kg NH4+-N ha-1)
12/01/2013
03/01/2014
06/01/2014
e)
Soil N2O flux (g N2O-N ha-1 d-1)
Observed
Simulated
f)
Cumulative N2O-N loss (kg N ha-1)
Observed
Simulated
12/01/2013
01/01/2014
02/01/2014
03/01/2014
04/01/2014
05/01/2014
06/01/2014
07/01/2014
Date

Fig. 3

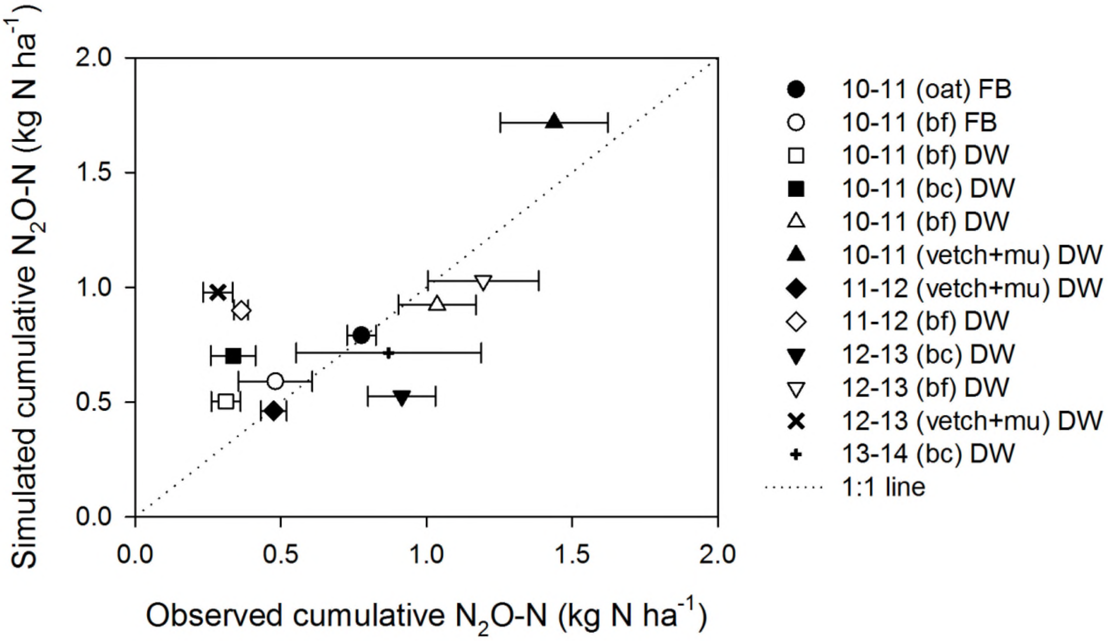
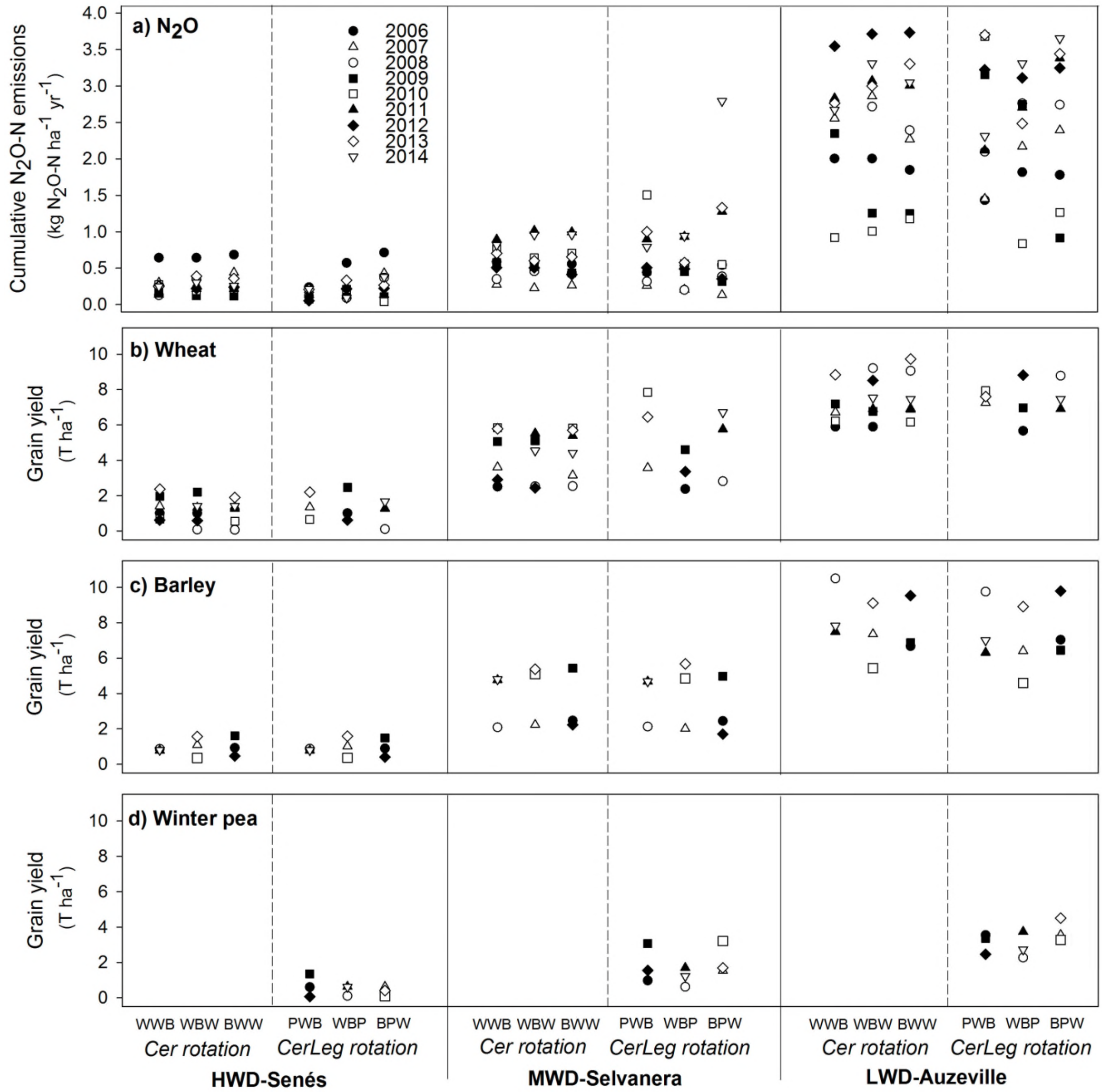

Simulated cumulative N_2O-N (kg N ha^{-1})
Observed cumulative N_2O-N (kg N ha^{-1})
0.0
0.5
1.0
1.5
2.0
10-11 (oat) FB
10-11 (bf) FB
10-11 (bf) DW
10-11 (bc) DW
10-11 (bf) DW
10-11 (vetch+mu) DW
11-12 (vetch+mu) DW
11-12 (bf) DW
12-13 (bc) DW
12-13 (bf) DW
12-13 (vetch+mu) DW
13-14 (bc) DW
1:1 line

Fig. 4



a) N2O
b) Wheat
c) Barley
d) Winter pea
Cumulative N2O-N emissions (kg N2O-N ha-1 yr-1)
Grain yield (T ha-1)
2006
2007
2008
2009
2010
2011
2012
2013
2014
WWB WBW BWW
PWB WBP BPW
Cer rotation
CerLeg rotation
HWD-Senés
MWD-Selvanera
LWD-Auzeville

Fig. 5

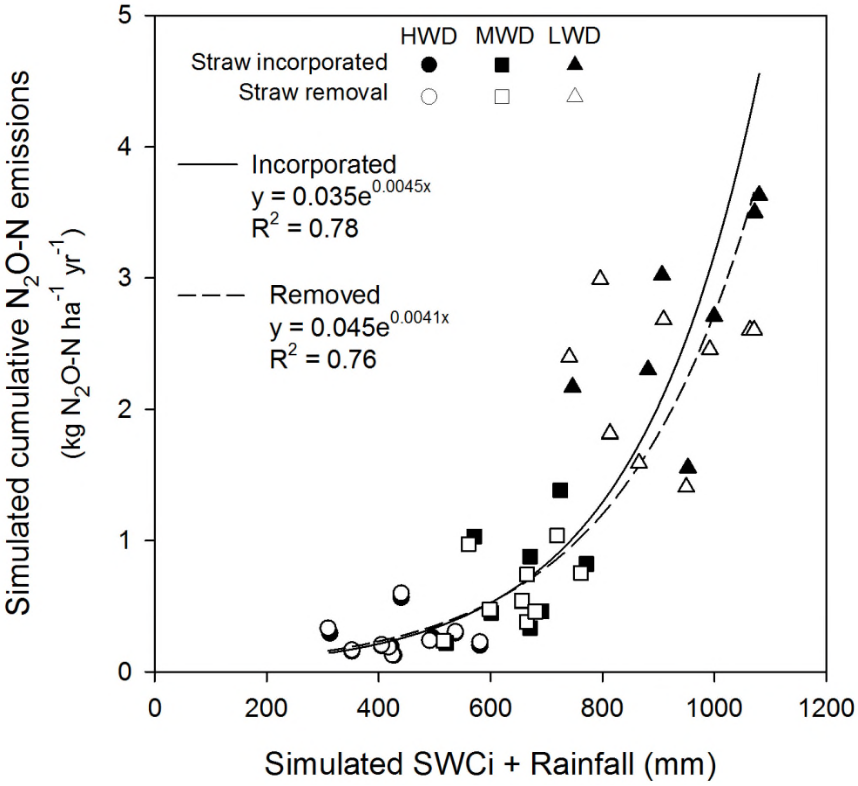

HWD MWD LWD
Straw incorporated
Straw removal
Incorporated
y = 0.035e^0.0045x
R^2 = 0.78
Removed
y = 0.045e^0.0041x
R^2 = 0.76
Simulated cumulative N2O-N emissions
(kg N2O-N ha^-1 yr^-1)
Simulated SWCi + Rainfall (mm)
0
1
2
3
4
5
0
200
400
600
800
1000
1200

Fig. 6

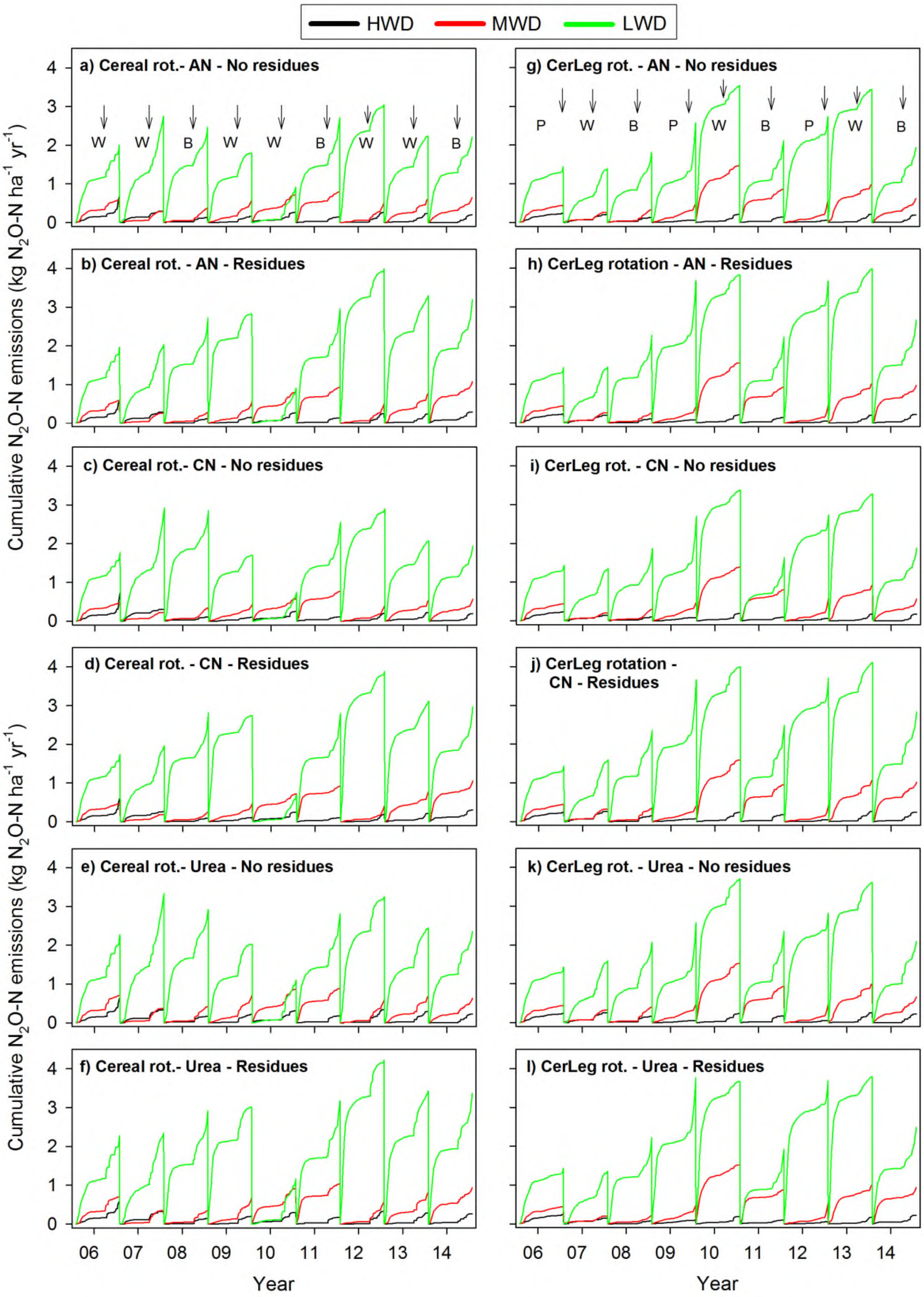

HWD
MWD
LWD
a) Cereal rot.- AN - No residues
W W B W W B W W B
b) Cereal rot. - AN - Residues
c) Cereal rot.- CN - No residues
d) Cereal rot. - CN - Residues
e) Cereal rot.- Urea - No residues
f) Cereal rot.- Urea - Residues
g) CerLeg rot. - AN - No residues
P W B P W B P W B
h) CerLeg rotation - AN - Residues
i) CerLeg rot. - CN - No residues
j) CerLeg rotation - CN - Residues
k) CerLeg rot. - Urea - No residues
l) CerLeg rot. - Urea - Residues
Cumulative N_2O-N emissions (kg N_2O-N ha^{-1} yr^{-1})
06 07 08 09 10 11 12 13 14
Year

Fig. 7

Table S1. Crop management practices carried out in the wheat phase of a wheat – sorghum – sunflower rotation with and without cover crops (BF, bare fallow; CC, cover crops) (per order: vetch+phacelia, sorghum volunteers and berseem clover), where daily N_2O measurements were carried out in LWD-Auzeville (SW, France).

Management practice	Cover crops use		Date	Type of implement or input	Amount of inputs	
	BF	CC			BF	CC
Durum wheat crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)						
Previous cash crop residues incorporation	X	X	09/15/2010	Disk tandem		
Tillage		X	09/16/2010	Rotary harrow		
Sowing		X	09/16/2010	Berseem clover cv. Miriam		18 kg ha^{-1}
Tillage	X	X	10/29/2010	Rotary harrow		
Sowing	X	X	12/07/2010	Durum wheat cv. Isildur	477 seeds m^{-2}	477 seeds m^{-2}
N fertilization	X	X	04/04/2011	Ammonium nitrate	100 kg N ha^{-1}	100 kg N ha^{-1}
N fertilization	X	X	04/27/2011	Ammonium nitrate	60 kg N ha^{-1}	60 kg N ha^{-1}
Harvest	X	X	07/05/2011	Medium-sized combine		
Durum wheat crop grown in the 2012-13 season preceded by bare fallow (BF) and cover crop (CC)						
Sowing (undersown)		X	06/06/2012	Berseem clover cv. Miriam		15 kg ha^{-1}
Previous cash crop residues incorporation	X		09/17/2012	Disk tandem		
Tillage	X	X	10/24/2012	Disk tandem		
Tillage	X	X	11/18/2012	Rotary harrow		
Sowing	X	X	11/19/2012	Durum wheat cv. Isildur	345 seeds m^{-2}	345 seeds m^{-2}
N fertilization	X	X	03/26/2013	Ammonium nitrate	107 kg N ha^{-1}	107 kg N ha^{-1}
N fertilization	X	X	04/29/2013	Ammonium nitrate	54 kg N ha^{-1}	54 kg N ha^{-1}
Harvest	X	X	07/18/2013	Medium-sized combine		
Durum wheat crop grown in the 2013-14 season preceded by a cover crop (CC)						
Sowing (undersown)		X	05/07/2013	Alfalfa+Clovers mixture		
Cover crop termination		X	12/04/2013	Mower		
Tillage		X	12/05/2013	Disk tandem		
Tillage		X	12/12/2013	Rotary harrow		
Sowing		X	12/12/2013	Durum wheat cv. Isildur		
N fertilization		X	03/14/2014	Ammonium nitrate		90 kg N ha^{-1}
N fertilization		X	04/09/2014	Ammonium nitrate		30 kg N ha^{-1}
N fertilization		X	05/04/2014	Ammonium nitrate		31 kg N ha^{-1}
Harvest		X	07/15/2014	Medium-sized combine		

Table S2. Crop management practices carried out in the wheat and faba bean phases of a wheat – sunflower – faba bean rotation with and without cover crops (BF, bare fallow, CC, cover crops) (per order: vetch+oat, oat and vetch+mustard), where daily N_2O measurements were carried out in LWD-Auzeville (SW, France).

Management practice	Cover crops use		Date	Type of implement or input	Amount of inputs	
	BF	CC			BF	CC
Faba bean crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)						
Previous cash crop residues incorporation	X	X	09/15/2010	Disk tandem		
Tillage		X	09/16/2010	Rotary harrow		
Sowing		X	09/16/2010	Oat cv. Cadence		19 kg seeds ha^{-1}
Tillage	X		10/29/2010	Rotary harrow		
Cover crop incorporation		X	12/06/2010	Moldboard plough		
Tillage		X	12/09/2010	Rotary harrow		
Sowing	X	X	12/13/2010	Faba bean cv. Iréna	26 seeds m^{-2}	26 seeds m^{-2}
Harvest	X	X	07/05/2011	Medium-sized combine		
Durum wheat crop grown in the 2010-11 season preceded by bare fallow (BF) and cover crop (CC)						
Previous cash crop residues incorporation	X	X	07/28/2010	Disk tandem		
Tillage		X	08/16/2010	Disk tandem		
Tillage		X	09/06/2010	Rotary harrow		
Sowing		X	09/06/2010	Mustard cv. Ascot		24 kg seeds ha^{-1}
Irrigation		X	09/09/2010	Large-volume sprinkler		30 mm
Tillage	X		10/29/2010	Rotary harrow		
Cover crop incorporation		X	12/06/2010	Moldboard plough		
Sowing	X		12/07/2010	Durum wheat (mixture of 4 cv.)	404 seeds m^{-2}	
Tillage		X	12/09/2010	Rotary harrow		
Tillage		X	12/12/2010	Rotary harrow		
Sowing		X	12/13/2010	Durum wheat (mixture of 4 cv.)		404 seeds m^{-2}
N fertilization	X	X	04/04/2011	Ammonium nitrate	50 kg N ha^{-1}	90 kg N ha^{-1}
N fertilization	X	X	04/27/2011	Ammonium nitrate	50 kg N ha^{-1}	50 kg N ha^{-1}
Harvest	X	X	07/05/2011	Medium-sized comine		
Durum wheat crop grown in the 2011-12 season preceded by bare fallow (BF) and cover crop (CC)						
Previous cash crop residues incorporation	X	X	08/01/2011	Disk tandem		
Tillage		X	08/01/2011	Rotary harrow		
Sowing		X	08/01/2011	Vetch cv. Bingo + Mustard cv. Ascot		20+5 kg seeds ha^{-1}
Tillage	X		09/01/2011	Disk tandem		

Tillage	X		09/30/2011	Disk tandem		
Cover crop termination		X	10/20/2011	Mower		
Tillage		X	10/21/2011	Disk tandem		
Tillage	X	X	11/14/2011	Rotary harrow		
Sowing	X	X	11/14/2011	Durum wheat (mixture of 4 cv.)	316 seeds m^{-2}	316 seeds m^{-2}
N fertilization	X	X	03/13/2012	Ammonium nitrate	52 kg N ha^{-1}	82 kg N ha^{-1}
N fertilization	X	X	04/23/2012	Ammonium nitrate	30 kg N ha^{-1}	51 kg N ha^{-1}
Harvest	X	X	07/03/2012	Medium-sized combine		
Durum wheat crop grown in the 2012-13 season preceded by a cover crop (cc)						
Previous cash crop residues incorporation		X	08/01/2012	Disk tandem		
Tillage		X	08/17/2012	Disk tandem		
Tillage		X	08/23/2012	Rotary harrow		
Sowing		X	08/23/2012	Vetch cv. Bingo + Mustard cv. Ascot		25+5 kg seeds ha^{-1}
Irrigation		X	09/05/2012	Large-volume sprinkler		23 mm
Cover crop termination		X	10/24/2012	Mower		
Tillage		X	10/24/2012	Disk tandem		
Tillage		X	11/19/2012	Rotary harrow		
Sowing		X	11/19/2012	Durum wheat (mixture of 4 cv.)		316 seeds m^{-2}
N fertilization		X	03/26/2013	Ammonium nitrate		64 kg N ha^{-1}
N fertilization		X	04/29/2013	Ammonium nitrate		43 kg N ha^{-1}
Harvest		X	07/18/2013	Medium-sized combine		

Table S3. Analysis of variance (*P* values) of the simulated cumulative N_2O emissions from nitrification and denitrification, total N_2O emissions, N_2O ratio (denitrification) and wheat yield in a cereal- (wheat-wheat-barley) and a cereal-legume (winter pea-wheat-barley) based rotation with different crop residue management (removed vs. incorporated) and N fertilizer types (ammonium nitrate, calcium nitrate, and urea) in the three sites over the 2006-2014 period. Note that for each year, the three phases of each rotation were taken into account in the statistical analysis related to N_2O.

Effect	N_2O nitrification	N_2O denitrification (1)	Total N_2O (2)	N_2O ratio (1):(2)	Wheat yield
Site (S)	<0.001	<0.001	<0.001	<0.001	<0.001
Rotation (Rot)	<0.001	0.625	0.486	0.187	0.038
Fertilizer (F)	<0.001	0.471	<0.001	<0.001	0.546
Residues (Res)	<0.001	<0.001	<0.001	0.300	0.555
Year (Y)	<0.001	<0.001	<0.001	<0.001	
S*Rot	0.003	0.005	0.003	0.251	0.050
S*F	0.001	0.987	0.704	<0.001	0.993
S*Res	0.006	<0.001	<0.001	0.001	0.924
S*Y	<0.001	<0.001	<0.001	<0.001	
Rot*F	<0.001	0.490	0.003	<0.001	0.531
Rot*Res	0.328	0.649	0.555	0.637	0.757
Rot*Y	0.006	<0.001	<0.001	0.005	
Res*F	<0.001	0.984	0.028	<0.001	0.576
Y*F	0.977	0.999	0.999	0.677	
Y*Res	0.011	<0.001	<0.001	0.169	
S*Rot*Y	<0.001	<0.001	<0.001	<0.001	
S*Rot*Res	0.998	0.910	0.926	0.783	0.961
S*Y*Res	0.975	0.004	0.033	0.010	
S*Rot*F	0.001	0.991	0.801	<0.001	0.995
S*Y*F	1.0	1.0	1.0	0.264	
S*Res*F	0.541	0.978	0.854	0.002	0.997
Rot*Y*F	0.959	1.0	1.0	0.713	
Rot*Y*Res	0.998	0.957	0.974	0.974	
Rot*Res*F	<0.001	0.603	0.345	<0.001	0.857
Y*Res*F	1.0	1.0	1.0	0.980	
S*Rot*Y*F	1.0	1.0	1.0	0.289	
S*Rot*Y*Res	1.0	0.999	1.0	1.0	
S*Rot*Res*F	0.216	1.0	0.997	0.001	0.998
S*Y*Res*F	1.0	1.0	1.0	0.991	
Rot*Y*Res*F	0.997	1.0	1.0	0.847	
S*Rot*Y*Res*F	1.0	1.0	1.0	0.992	